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Civilian Radioactive Waste Management System
Management & Operating Contractor

Calculation Method for the Projection of Future Spent Nuclear Fuel Discharges

TDR-WAT-NU-000002 Rev 01

February 2002

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DISCLAIMER

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REVISION HISTORY

Revision Number	Effective Date	Description of Change
00	February 2001	Initial Issue
01	February 2002	Added reactor-specific burnup limits based on maximum enrichment limits, added ability to accommodate possible future nuclear plant power level uprates, and updated the projection results. Made minor change to report title

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ACRONYMS AND ABBREVIATIONS

Acronyms

BWR	boiling water reactor
CRWMS	Civilian Radioactive Waste Management System
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
MOX	mixed (plutonium/uranium) oxide (Pu-enriched UO_2 fuel)
MTU	metric tons of uranium
NRC	U.S. Nuclear Regulatory Commission
PWR	pressurized water reactor
SNF	spent nuclear fuel

Abbreviations

GWd/MTU	gigawatt-days per metric ton of uranium
kWhe	kilowatt-hours electrical
MWd/MTU	megawatt-days per metric ton of uranium
MWe	megawatt-electrical
TWhe	Terawatt-hours electrical

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GLOSSARY

batch average burnup	The average burnup of all spent nuclear fuel assemblies (a discharge batch) permanently discharged at the same time.
capacity factor	The ratio of actual energy production to the maximum potential energy production, if at 100 percent of rated capacity, during a defined period.
energy balance factor	A single factor that adjusts the quantities of all projected discharges (except the first and last) in order to adjust the total thermal energy produced by the fuel so that it equals the thermal energy needed to generate the total projected electrical energy.
implied capacity factor	The capacity factor implied (i.e., calculated) from the utility five-discharge projection.

utility five-discharge projection: In the periodic RW-859 surveys, the utilities provide the projected amounts, burnups, enrichments and dates for the next 5 discharges for each of their reactors. As described in this report, these 5 utility-projected discharges are the starting point for the projection of all subsequent discharges through to the final discharge at operating license expiration.

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1. PURPOSE

This report describes the calculation method developed for the projection of future utility spent nuclear fuel (SNF) discharges in regard to their timing, quantity, burnup, and initial enrichment. This projection method complements the utility-supplied RW-859 data on historic discharges and short-term projections of SNF discharges by providing long-term projections that complete the total life cycle of discharges for each of the current U.S. nuclear power reactors. The method was initially developed in mid-1999 to update the SNF discharge projection associated with the 1995 RW-859 utility survey (CRWMS M&O 1996), and was further developed as described in Rev. 00 of this report (CRWMS M&O 2001a). Primary input to the projection of SNF discharges is the utility projection of the next five discharges from each nuclear unit, which is provided via the revised final version of the Energy Information Administration (EIA) 1998 RW-859 utility survey (EIA 2000a).

The projection calculation method is implemented via a set of Excel 97 spreadsheets. These calculations provide the interface between receipt of the utility five-discharge projections that are provided in the RW-859 survey, and the delivery of projected life-cycle SNF discharge quantities and characteristics in the format requisite for performing logistics analysis to support design of the Civilian Radioactive Waste Management System (CRWMS).

Calculation method improvements described in this report include the addition of a reactor-specific maximum enrichment-based discharge burnup limit. This limit is the consequence of the enrichment limit, currently 5 percent, which is imposed as a Nuclear Regulatory Commission (NRC) license condition on nuclear fuel fabrication plants. In addition, the calculation method now includes the capability for projecting future nuclear plant power upratings, consistent with many such recent plant uprates and the prospect of additional future uprates. Finally, this report summarizes the results of the 2002 Reference SNF Discharge Projection.

In accordance with the technical work plan covering this report (CRWMS M&O 2001b), this document has been classified as non-QA.

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2. SUMMARY OF THE PROJECTION CALCULATION METHOD

Input to the calculation includes the utility-supplied projection of the burnups, quantities, and timing of the next five discharges for each operating reactor. User input includes the global average annual increase in average discharge burnup, the maximum value of the batch-average discharge burnup for the two reactor types, and the maximum licensed enrichment at nuclear fuel fabrication plants.

Among the primary goals of the utility SNF discharge projection is recognizing and replicating the principal trends evident in the historic discharges and in the utility-projected future discharges. The most important of these trends include the general utility adoption of 18 or 24 month cycle durations between refuelings, and a consistent long-term trend of increasing discharge burnups. Accordingly, the first calculation for each reactor consists of calculating future discharge dates using the cycle durations obtained by inspection of the discharge periods between the five utility-projected discharge dates. An appropriate reference burnup for each reactor is then calculated from the utility-projected burnups, and this value is extrapolated to the time of each future discharge at the user-specified global average burnup increase rate. The discharge quantities are calculated next, assuming the continuation of the average capacity factor implied by the utility projection. An energy balance factor is then applied (initially 1.0) to the discharge quantities to assure consistency with a user-chosen EIA projection of total nuclear electric energy generation. The user subsequently iterates, manually, to converge on the energy balance factor that produces the correct total thermal energy and the related SNF discharge quantities needed to generate the electrical energy that is consistent with the chosen EIA projection of total electrical energy generation. The initial enrichment of the discharged fuel is then calculated using an EIA-developed correlation of initial enrichment as a function of burnup and refueling fraction (DOE 1997). Finally, the distribution of assembly burnups about the batch-average is calculated for each discharge of every reactor, using a data-based burnup distribution pattern.

The output of the calculation is the burnup distribution, number of assemblies, metric tons of uranium (MTU), enrichment, and date of each projected discharge for each reactor, through its final shutdown at the expiration of its operating license. This calculation provides one of the principal inputs needed to perform the SNF delivery, container loading, and logistic analyses that support design of the CRWMS.

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3. ASSUMPTIONS AND REQUIREMENTS

The calculation of projected civilian SNF discharges is based on the following assumptions and requirements:

- The calculation of the projection is based on energy balance, rather than on reactor physics-based nuclear fuel cycle methods, which also provide an energy balance, but are considerably more complex and difficult to understand. In general, these alternative methods are equivalent if the initial enrichments are chosen correctly in the energy-balance method. Since the enrichment correlation used to assign enrichments is based on actual discharges, there is reasonable assurance that the energy-balance method used for this calculation procedure gives results equivalent to a reactor physics-based method.

- The long-term projection is to begin with, and directly use, the utility-supplied RW-859 projections for their next five discharges. The projection calculations are an extrapolation of the utility projections with regard to the timing, magnitude, and trend of future discharges.

- Adjustments of the utility-supplied projections are to be made, in general, as equal fractional adjustments to all utility projections so as to preserve inter-utility differences related to plant operating capacity factors and fuel cycle management. The principal adjustment made is to adjust projected discharge quantities by a common factor in order to provide total energy consistency with the EIA projection of overall nuclear electric generation. Because of this discharge quantity adjustment, it is also necessary to make small adjustments of the utility-projected enrichments for those discharges. The energy-based adjustment is made to all projected discharges except the first utility-projected discharge (because it normally includes some actual energy production prior to the start of the projection) and the final full core discharge (which is a fixed quantity established by reactor design).

- There are two primary assumptions in the projection of future SNF discharge quantities and characteristics: the total nuclear energy generated, which largely determines the total amount of radioactivity generated; and the discharge burnup, which largely determines the quantity of radioactivity in individual SNF assemblies. The total projected quantity of SNF (in MTU) varies in direct proportion to the projected total energy (in megawatt-days [MWd]), and inversely with the projected average burnup (in MWd/MTU). The total energy to be generated is determined by two subsidiary assumptions: the average capacity factor of operating reactors, and the end-of-life shutdown date of each reactor. With regard to average capacity factors, this projection methodology uses annual average capacity factors developed from current EIA forecasts of nuclear electric generation, which are based on EIA's extrapolation of actual historic data. The reactor shutdown date is traditionally assumed to be that of the NRC operating license termination date for each reactor.

Recently, the awarding of 20-year NRC operating life extensions for several plants, with the prospect of many additional 20-year extensions, has complicated the projection process. This is being addressed by making several alternative projections with different numbers of reactors assumed to receive extensions. The projection of discharge burnups is done by an extrapolation of historical rates of increasing burnup. The nature of this extrapolation is under user control, but the particular assumptions being used in this report are based on the plans of the U.S. utility industry for the demonstration and ultimate achievement of increased burnup. The body of this report describes the burnup assumptions used. Appendix A provides a fundamental analysis and evaluation of near-term and long-term utility incentives and constraints for increased SNF burnups.

The projection of the timing and level of future discharge burnups involves one of the most important sets of assumptions for a projection. The burnup assumptions affect the projected discharge quantities inversely. More importantly, the burnup assumptions directly affect the projected thermal and radiological characteristics of the SNF and thus impact projected transport cask and waste package loadings, and ultimately the scheduling and logistics of repository operation and emplacement. For this reason, particular attention has been given to the factors and assumptions underlying the projection of future burnups, and these are discussed in Appendix A in detail. The key points developed in Appendix A are as follows:

1. There is a well-established historic trend of increasing average SNF discharge burnups, at a recent rate of more than 2 percent/yr. The annual averages of utility projections for their next five discharges continue to show increasing burnups.

2. The Electric Power Research Institute's (EPRI) Robust Fuel Project has established demonstration targets that support average discharge burnups of 57,000 MWd/MTU for boiling water reactors (BWR) and 62,000 MWd/MTU for pressurized water reactors (PWR). Attainment of these burnups relative to current burnups would result in fuel cost savings in the range of 0.15 to 0.3 mills/kilowatt-hour electrical (kWhe), equivalent to \$1.1 to \$2.2 million/yr for a 1000 megawatts electrical (MWe) plant. According to ongoing electric utility deregulation practices, these savings would accrue directly to utilities, giving utilities significant direct incentives to continue to increase discharge burnups at a rate consistent with demonstrating continuing fuel integrity, and to increase nuclear plant capacity factors.

3. There is a current limit on attainable burnup, imposed by the current 5 percent maximum U-235 enrichment in the NRC licenses for nuclear fuel fabrication plants. The maximum batch-average burnup for a given maximum fuel enrichment is reactor-specific because of different fuel designs and different operating conditions such as capacity factors and refueling intervals. The EPRI target burnups are generally compatible with the PWR and BWR burnups attainable with the current 5 percent enrichment limit. The overall maximum batch-average burnup for each reactor is the lower of the EPRI target burnup or the reactor-specific enrichment-limited maximum burnup. Because of the compatibility with enrichment limits and

the utility financial incentives to increase burnups, ultimate attainment of EPRI target burnups appears to be a reasonable assumption for the projection of future discharge burnups. A 1 percent annual increase in average burnups would result in the initial discharges of EPRI target burnups in about 2015, providing considerable time for demonstration of acceptable fuel clad integrity. The 1 percent/yr rate is less than both the historic and the most recent utility-projected increase rates. However, this appears appropriate in view of the progressive decrease in economic incentive as burnups increase.

4. An increase in the maximum licensed enrichment to 5.5 percent would permit an increase in discharge burnups of up to 10,000 MWd/MTU, and additional fuel cost savings in the range of $0.5 to $1.0 m/yr for a 1000 MWe plant, under current economic conditions. Such an incentive is probably sufficient to interest at least some utilities, so that there is a possibility that burnups could ultimately go above the current EPRI targets. However, given the relatively long time for getting to, and then beyond, the EPRI target burnups, the related technical uncertainties, and the possibility of adverse cost changes that reduce or eliminate the apparent current incentives, it does not appear prudent to project average discharge burnups above the EPRI target burnup levels at this time.

5. The burnups achievable at a 5.5 percent enrichment limit result in fuel costs within roughly 1 percent of minimum possible fuel costs under current economic conditions, and these could be at or above the burnups at which future minimum fuel costs are achieved. The rapidly diminishing incentives and the increased enrichments needed to go to even higher burnups probably mean that the practical upper limit on burnup is the burnup achievable at 5.5 percent enrichment.

6. When the batch-average burnup is at the EPRI batch-average PWR target burnup of 62,000 MWd/MTU, the maximum assembly-average burnup is about 71,000 MWd/MTU, and the maximum rod-average burnup is about 75,000 MWd/MTU. Thus, a suitable maximum assembly burnup that could be used for the design of repository facilities would be in the range of 71,000 to 75,000 MWd/MTU, with the current 5.0 percent enrichment limit. However, an additional 10,000 MWd/MTU could be achieved in the future, if the enrichment limit were raised to 5.5 percent. The incremental cost of additional shielding is quite small if included in the original construction. It would therefore be prudent for shielding designers to consider using 85,000 MWD/MTU as the maximum assembly-average burnup, coupled with a suitably short cooling time, such as 5 years, for the design of shielding in fixed repository facilities.

In conclusion, the current fuel fabrication plant license limit of 5 percent enrichment, the related target burnups of the EPRI Robust Fuel Project, and the assumed gradual (1 percent/year) approach to these target burnups provide a basis for the projection of spent fuel discharge burnups that is consistent with historic industry experience and realistic future goals. Unless and until the 5 percent nuclear fuel fabrication plant enrichment limit is increased, it is reasonable to expect only relatively few "outlier" assemblies with burnups above the EPRI maximum assembly average discharge burnup targets. Only after fuel fabricators relicense their plants for enrichments above 5 percent, and utilities begin higher-burnup demonstration programs, would it be reasonable to begin projecting meaningful quantities of SNF with burnups above the current EPRI target levels. The practical upper limit on burnup is probably the burnup achievable at 5.5 percent enrichment.

4. COMPUTER SOFTWARE

The series of calculations are implemented in two Excel 97 workbooks, each containing multiple spreadsheets. The first workbook characterizes the utility projections of their next 5 discharges, which are then used as input to the second workbook. The second workbook does the projection using one particular set of projection assumptions. Because there are multiple alternative assumptions, there can be multiple second workbooks, one of which would be considered the baseline case for a particular set of projections. The second workbook will be cited generically in this report as the Projection Workbook. The Projection Workbook includes one macro that calculates the burnup distributions and performs the data sorting. This provides an output format consistent with that needed to perform the SNF delivery, selection, container loading, and logistics analyses that support design of the CRWMS.

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5. CALCULATION PROCESS

The projection method fully adopts the utility forward projections of the next five discharges for each plant with respect to timing and burnup. The individual discharge quantity projections are also fully adopted, initially, to reflect individual plant capacity factor expectations, but are subject to a later aggregate, energy-based adjustment. Specifically, the projected discharge quantities of all plants will be adjusted by the same common energy balance factor. This single, common adjustment will enable the total thermal energy production implied by the discharge quantities and burnups to be consistent with the EIA projection of total nuclear electric energy production from all the reactors. The usage of this single common adjustment factor for all reactors assures preservation of the inter-utility differences evident in the utility projections.

The remainder of this section provides a summary of the steps in the projection, followed by a detailed description of each step. In summary, the principal steps of the projection are:

1. Characterize the refueling interval, discharge quantity, burnup and its trend, and implied capacity factor for each reactor, based on the utility's projection of five forward discharges for that reactor.

2. Project the dates of future discharges through the final discharge at the plant end-of-life shutdown, starting from the date of the fifth utility-projected refueling, using the utility-defined refueling interval.

3. Project the burnups of all future discharges, using the utility-projected burnups and trends. Projections of discharge burnups recognize the goals of the EPRI Robust Fuels Project[1], which targets maximum rod-average burnups of 75,000 and 70,000 MWd/MTU for PWRs and BWRs respectively. These correspond to batch-average discharge burnups of approximately 62,000 and 57,000 MWd/MTU for PWRs and BWRs respectively. In order to reflect the time it takes to first demonstrate and then achieve high burnups, it is assumed that batch-average burnups will increase at an annual rate such that the latter batch-average burnups will be reached in the 2015 time frame by one or more reactors with the highest discharge burnups. An annual average increase rate of about 1 percent achieves this objective and has been used for this projection. There will be a corresponding gradual increase in initial fuel enrichment. The limits on batch-average burnups were set at the lower of 1) the EPRI goal of 57,000 MWd/MTU for BWRs and 62,000 MWd/MTU for PWRs, or 2) the plant-specific maximum burnup achievable at the user-specified enrichment limit, currently 5 percent.

4. Project the assemblies and MTU discharged at each projected discharge date (Step 2), for each reactor, maintaining the individual plant operating capacity factors (Step 1,

[1] Personal communication between Odelli Ozer of EPRI and Barrie McLeod of the Management and Operating Contractor (M&O), 11/17/99.

above) and using the foregoing burnup projection (Step 3). Initially, the user sets the Energy Adjustment Factor to 1.0.

5. Determine the overall Energy Adjustment Factor on discharge quantities that is required for energy consistency, using the total energy production implied by the discharge quantities and burnups, the EIA projection of nuclear electric production, and the electric and thermal capacities of each plant. This is accomplished as follows: after each projection iteration, the current Energy Adjustment Factor is multiplied by a factor calculated by the program, in order to provide the user with an estimate of a new Energy Adjustment Factor. The user can then manually input this new Factor for a repeat of Step 4, above. The user repeats Steps 4 and 5 manually until the multiplying factor remains sufficiently close to 1.0 between iterations, and the Energy Adjustment Factor has therefore converged. At this point, an energy balance has been achieved between the EIA-based nuclear-electric generation projection and the thermal energy generation implied by the projected SNF discharge quantities and burnups.

6. Project the initial enrichment of each discharge using an EIA correlation of initial enrichment as a function of average discharge burnup and refueling fraction, adjusted for consistency with the five utility-projected enrichments.

7. Calculate the distribution of assembly burnups about the batch average burnup.

The foregoing summary of each step in the projection process is deliberately brief. Additional details of the calculations within each step are described in the following sections.

5.1. CHARACTERIZE THE UTILITY FIVE-DISCHARGE PROJECTIONS

The quantities, burnups, enrichments, and refueling dates for the five utility-projected discharges occurring at the beginning of the projection period are provided to the U.S. Department of Energy (DOE) via the RW-859 survey, and are summarized in the *Report on the Final 1998 RW-859 Data Set* (CRWMS M&O 2001c).

Projection of discharges beyond the first five utility-projected discharges requires a determination for each plant of the cycle duration (calendar time interval between refuelings), an appropriate burnup reference point from which to project future burnup increases, and the average plant operating capacity factor.

The cycle duration is determined from the utility-projected refueling dates, generally as the average interval between utility-projected refuelings, rounded to the nearest full month. However, this is done on a case-by-case basis because some plants are still in a transition to an extended cycle that is achieved only in the last two or three utility-projected cycles. The resulting cycle duration is used directly as the basis for the projection of future discharge dates, except for the date of the discharge prior to shutdown.

The utility-projected burnup data is used directly during the utility projection period. It is also used to calculate a burnup reference point for the subsequent projection of discharge burnups. A least-squares linear fit is calculated using the 5 utility discharge burnups, and the fit value of burnup at the fifth utility discharge is used as the burnup reference point for the post-utility burnup projections (described in a later subsection). This best-fit fifth discharge burnup value, rather than the utility-projected fifth discharge burnup, is used to smooth out the variability that is evident in many of the utility burnup projections.

An implied plant-specific capacity factor is calculated as described below, based on the utility projections of cycle time, discharge burnups, and quantities. This value is then assumed to hold constant and is used for the remainder of the projection period. This sustains the utility-implied capacity factor for the whole projection period, maintaining the relative differences between utilities, and is subject only to the effective adjustment of all capacity factors on the basis of overall energy balance. The calculation of the average capacity factor that is implied by the utility-supplied projection data is based on a steady-state energy balance and is:

$$\text{Implied Capacity Factor} = \text{CF}$$
$$= \frac{\text{Burnup (MWd/MTU) x Ass'ys Discharged x MTU/ass'y}}{\text{Cycle Length (days) x Reactor Thermal Power (MWt)}} \qquad \text{(Eq. 1)}$$

The cycle ending with the first discharge covers some energy produced prior to the start of the projection period. For this reason, the projection methodology uses the utility projection for the first discharge quantity without modification, excluding it from the energy balance adjustment. Thus, the above capacity factor calculation for each reactor is based on the average assemblies discharged, cycle lengths, and burnups over the second to fifth utility discharge projections.

The various calculations that characterize the utility discharge projections are performed in the first Excel workbook, FINAL_UTIL_SNF_PROJ_1998.xls. The key results are copied manually to the INPUT sheet of the particular Projection Workbook embodying the additional assumptions to be used for a particular projection. Typical user assumptions can include changing (shortening or extending) Nuclear Regulatory Commission (NRC) operating license termination dates, annual burnup increase rates, maximum PWR and BWR batch-average burnup limits, the maximum licensed enrichment at fuel fabrication plants, and projected nuclear plant capacity factors. Assuming that all projections would use the utility discharge projection, all Projection Workbooks would use the key results of the FINAL_UTIL_SNF_PROJ_1998.xls workbook. Each different projection would require a different Projection Workbook with a unique name, in order to save the results. However, each such projection would typically be developed by appropriately modifying and renaming an existing Projection Workbook, such as the workbook that is considered to be the baseline projection for a particular set of projections.

5.2. PROJECT THE REFUELING TIMES THROUGH FINAL SHUTDOWN

Beyond the period of the utility five-discharge projection, the refueling cycle duration evident in the utility projection period is maintained throughout the projection period except just prior to the final shutdown. The discharge date projection begins by adding the refueling cycle duration to the utility date for the fifth utility-projected discharge. The projection is continued by repetitive additions of the refueling interval to the prior discharge date, until the refueling prior to the final shutdown date. This preserves the seasonality of refueling shutdowns that is evident with the 18 and 24 month cycle durations that predominate in the utility projections.

The last cycle duration prior to final shutdown will typically be different than the preceding cycle durations, given that the license termination dates are normally not naturally compatible with the sequence of refueling outage dates. There is no utility data on the fuel cycle appropriate for a planned final shutdown. This is because all of the final shutdowns to date occurred in circumstances that did not allow for long-range planning. In the absence of utility data, it is assumed that the pre-shutdown fuel cycle will operate without any special measures, except those that are necessary to ensure reasonable cycle durations just prior to final shutdown. If the prospective final cycle duration is from one-third to almost a normal cycle duration, the last two cycles are shortened equally, each having a duration of from two-thirds to almost-normal cycle duration, with the second of the two shortened cycles ending on the shutdown date. The projected discharge quantity for the two pre-final discharges, calculated later, will be proportionately less than the fuel discharge quantities associated with the normal cycle duration. In those cases in which the prospective final cycle would otherwise be unrealistically short, specifically less than or equal to one-third of the normal duration, the last cycle is simply extended such that the final cycle is up to four-thirds of the normal cycle duration. In this case, the projected discharge quantity for the pre-final discharge, calculated later, will be correspondingly larger than the fuel discharge quantities associated with the normal cycle duration.

The date of final shutdown of each nuclear plant is assumed to coincide with the termination date of the plant's NRC Operating License. Although these dates are reported in the RW-859 survey, the projection methodology uses the official NRC license termination dates, and also the official NRC-licensed thermal power, as published in NRC's Information Digest (NRC 2000). Recently, the initial 20-year operating license extensions have been granted by NRC, and the operators of many additional plants have stated their intention to seek 20-year extensions. This has introduced a major new variable into the projection process: the number and identity of plants assumed to receive 20-year extensions and operate for that additional period. Projections with different assumptions as to the number and identity of plants receiving 20-year extensions require manually changing the license termination dates of the appropriate plants on the INPUT sheet of the Projection Workbook and assigning different Projection Workbook file names for each such set of different license extension assumptions.

The calculation of projected discharge dates is performed on the DATES sheet of the Projection Workbook.

5.3. PROJECT BATCH-AVERAGE DISCHARGE BURNUPS THROUGH FINAL SHUTDOWN

The historical data on discharge burnup, such as the data on the annual average burnups for 1990 through 1998 in Table A-1 of Appendix A, shows evidence of continuing increases in overall average discharge burnup. This trend of increasing burnups is consistent with utility objectives of reducing fuel and operating costs, and reducing the quantities of spent fuel requiring storage. In most cases, the five utility-projected discharges also exhibit a general upward trend of increasing batch-average burnups. EPRI's Robust Fuel Project, which is collectively supported by utilities, has specific goals that include the design and demonstration of higher burnup fuels, with target maximum rod-average burnups of 75,000 and 70,000 MWd/MTU for PWRs and BWRs respectively. These maximum rod-average burnups correspond to maximum assembly-average burnups of approximately 71,400/66,000 MWd/MTU, and discharge batch-average burnups of about 62,000/57,000 MWd/MTU (P/BWR). Assuming achievement of the EPRI Project's goals, these burnups could be achieved by the lead plants, with progressive burnup increases, in 12 to 15 years. Currently, there is also a practical limit on achieving burnups much beyond these levels: fuel fabrication plants have all been designed and licensed by NRC to handle up to a maximum fuel enrichment of 5 percent U-235. Until sufficient incentives are identified to justify the costs of fabrication plant relicensing and modification, batch-average discharge burnups will be limited by the current inability to go above 5 percent initial enrichment during fabrication. The batch-average burnup achievable with a specified maximum enrichment is reactor-specific, depending upon cycle duration, expected capacity factor, and individual fuel design differences. Therefore, the limiting batch-average burnup is the lesser of 1) the appropriate EPRI target burnup, or 2) the reactor-specific maximum burnup achievable with the user-specified maximum enrichment. The method of calculating the enrichment-limited burnup is described as part of the discussion on enrichment calculation in the next section.

The burnup projection method adopts the utility burnup projections for the first five discharges and thereafter projects increasing burnups that reflect the foregoing factors. As described in Section 5.1, the reference point burnup for the post-utility projection for each reactor is calculated as the best-fit burnup value at the fifth utility-projected discharge. The burnup projection for each subsequent discharge batch of each reactor is performed by increasing this reference point burnup for that reactor at the user-input global annual rate that was chosen in order that the highest burnup discharges reach the burnup limits in approximately the year 2015. A 1.0 percent average annual increase in discharge burnups achieves this objective; consequently, a 1.0 percent rate was adopted for the baseline burnup projections. The projected discharge burnup for each discharge is calculated, based on its discharge date, starting with the reference point burnup for that reactor, compounded at the 1 percent/yr rate from the date of the fifth utility-projected discharge. Once the projected burnup for a particular reactor reaches the appropriate EPRI or enrichment-limited maximum burnup, it is capped at that limit. Because the global annual burnup increase rate is a user-specified input, sensitivity cases can be run using alternative assumptions for this parameter. The maximum EPRI PWR and BWR burnups, and the maximum enrichment, are also user-specified input, and thus can be changed to run alternative projections.

The projection of the average burnup of the final, full core discharge, B_{fin}, is given by:

$$B_{fin} = (1 + F_{pre}) \times B_{pre}/2 \qquad \text{(Eq. 2)}$$

Where:

F_{pre} = the refueling fraction of the pre-final discharge. Because the refueling fractions are not calculated until after the burnup is projected, this refueling fraction is assumed to be one-third (of the full core).

B_{pre} = the projected discharge burnup of the pre-final discharge.

The above formula reflects the fact that the final core discharge has a mixture of fully and partially-burned fuel, and is based on the linear reactivity decline fuel cycle model. The pre-final discharge burnup is used because it is the most representative of the maximally-burned portion of the final core.

The calculations of projected discharge burnups by cycle and the enrichment-limited burnups are performed on the BURNUPS sheet and on the INPUTS sheet of the Projection Workbook, respectively.

5.4 PROJECT THE DISCHARGE QUANTITIES AND ENRICHMENTS THROUGH FINAL SHUTDOWN

This section describes the calculation of the projected number of assemblies and MTU discharged, and the related initial enrichment, at each refueling, for each reactor. As noted above, once the projections of implied average capacity factor, cycle duration, and fuel burnup are made, the discharge quantities are predetermined by energy balance considerations and can be calculated directly. The basic relationship is obtained by restructuring Equation 1, above:

$$\text{Ass'ys Discharged} = \frac{\text{Reactor Thermal Power(MWt)} \times \text{Cycle Length (Days)} \times \text{Capacity Factor}}{\text{Burnup(MWd/MTU)} \times \text{MTU/Ass'y}} \qquad \text{(Eq. 3)}$$

The basic approach is to assume that the capacity factor implied by the utility's second through fifth discharge projections is maintained constant, thereby establishing the plant-specific reference value of: [Ass'ys Discharged x $\text{Burnup}]_{ref}/[\text{Cycle Length}]_{ref}$. Substituting this reference value into Equation 3 results in the following equation for calculating the Ass'ys Discharged as a function of the Cycle Length and the burnup projected above for each discharge prior to the final (full core) discharge:

$$\text{Ass'ys Discharged} = \frac{\text{Cycle Length}}{\text{Burnup}} \times \frac{[\text{Ass'ys Discharged} \times \text{Burnup}]_{ref}}{[\text{Cycle Length}]_{ref}} \qquad \text{(Eq. 4)}$$

This calculation of assemblies discharged is performed for each reactor, for every projected discharge after the five utility-projected discharges, except for the final discharge. The final discharge, occurring at final shutdown, equals the full core loading. The corresponding MTU discharges are calculated for each discharge for each reactor by multiplying the number of assemblies discharged by the average MTU per assembly, as determined from the utility discharge projections.

Once the quantities of discharged SNF have been projected, the corresponding initial enrichments can be calculated. The data on actual (historical) discharge burnups as a function of initial enrichment exhibits a wide scatter. This reflects the fact that in many cases fuel is discharged before its design burnup is reached, and in many other cases, assemblies are kept in the core after their design burnups have been reached. These variations from design burnup typically occur because of operational circumstances in which cycle capacity factors are influenced by unpredictable circumstances in plant and utility system operations, and/or in customer demand.

The method of projecting initial enrichment needs to reflect both design-basis enrichment/burnup relationships, and individual fuel design and plant operating differences. The burnup-enrichment correlation used was developed by EIA, consistent with actual historical discharged fuel data (DOE 1997), as follows:

For burnups up to 47,000 or 52,000 MWd/MTU for BWRs and PWRs, respectively:

Initial Enrichment = 1.018 + 0.0000457 x (1+F) x Burnup (BWR) (Eq. 5)
= 0.756 + 0.0000526 x (1+F) x Burnup (PWR) (Eq. 6)

For burnups above 47,000 or 52,000 MWd/MTU for BWRs and PWRs, respectively, the slope of the enrichment-burnup relationship increases to 0.000063 per MWd/MTU for both BWRs and PWRs, giving the following relationships:

Initial Enrichment = 1.018 + (1+F) x (0.000063 x Burnup - 0.8131) (BWR) (Eq. 7)
= 0.756 + (1+F) x (0.000063 x Burnup - 0.5408) (PWR) (Eq. 8)

Where: F = the Refueling Fraction = Ass'ys in Discharge Batch/Total Core Ass'ys
= Cycle Burnup/Discharge Burnup
Burnup is in MWd/MTU

The above enrichment correlations are for BWRs and PWRs as a class, but do not explicitly reflect the features of individual assembly designs, such as vendor differences, the use of stainless steel versus zircaloy spacers, and similar variations of design detail. Also, because enrichment is dependent upon refueling fraction, it is affected by utility operating practices that affect refueling fractions, including capacity factors and refueling cycle durations. In order to reflect these types of individual differences, the calculation of enrichments for each discharge batch uses the burnup-dependent second part of the above correlation to adjust for burnup and refueling fraction, but does not use the first part of the correlation, the "intercept" at zero burnup. Instead, it develops an intercept for each reactor, using the utility-projected enrichments described in the following paragraph.

Because there is no quantity adjustment of the first utility-projected discharge, the utility-projected enrichment is used without adjustment. For the second through the fifth utility-projected discharges, the utility-projected enrichments are used with an adjustment only for the difference between the utility-projected refueling fraction and the energy-adjusted refueling fraction. For all other discharges, a reactor-specific, zero-burnup intercept is determined by calculating the zero-burnup intercept for each of the five utility-projected discharges using the utility-projected enrichment less the second part of the BWR or PWR enrichment correlation, as appropriate. The reactor-specific intercept is the simple average of these five batch-specific intercepts. The initial enrichments for all remaining batches except the final discharge are thus calculated using this reactor-specific intercept plus the second, burnup dependent part of the above appropriate enrichment correlation. The enrichment of all fuel in the final discharge is calculated using this same procedure except that the burnup is set equal to the burnup of the pre-final discharge, and the refueling fraction is assumed to be one-third of the core. The resulting enrichment applies to all fuel in the final discharge, including the fuel that has been in-core for only one or two cycles. This assumption is conservative in that it may overestimate the enrichments utilities may ultimately use for the portion of the final core that is in-core for only one or two cycles, in order to minimize fuel costs for the final core. However, in the absence of data on how the fuel cycle leading up to the final discharge will be designed, the conservative approach for projecting final core enrichments has been used. The foregoing enrichment calculation is repeated for all reactors.

The plant-specific maximum burnup achievable with a maximum fuel fabrication plant enrichment, mentioned in the previous section, is calculated by restructuring Equations 7 and 8 to solve for Burnup, given the initial (maximum) enrichment. This calculation is facilitated by making the following substitution for F, the Refueling Fraction:

$$F = \text{Cycle Burnup/Discharge Burnup}$$

$$\text{Cycle Burnup} = \frac{\text{Reactor Power(MWt)} \times \text{Capacity Factor} \times \text{CycleDuration(days)}}{\text{Core Mass(MTU)}}$$

Making this substitution and restructuring Equations 7 and 8 results in the following:

$$\text{BMAX} = 15.873(\text{Emax} - \text{Eint} + 0.8131) - \text{CycleBurnup}(1 - 12.906/\text{BMAX})) \quad \text{(BWR)} \quad \text{(Eq. 9)}$$

$$= 15.873(\text{Emax} - \text{Eint} + 0.5408) - \text{CycleBurnup}(1 - 8.584/\text{BMAX})) \quad \text{(PWR)} \quad \text{(Eq. 10)}$$

Where:

BMAX is the maximum burnup (MWd/MTU) achievable at Emax

Emax is the maximum enrichment licensed for fuel fabrication plants

Eint is the reactor-specific zero-burnup enrichment intercept described above.

Because the above equations have a BMAX term on both sides of the equation, they are solved iteratively, using three sequential iterations to achieve a solution of acceptable accuracy. This calculation is done on the INPUTS sheet of the Projection Workbook.

Finally, the calculation of the discharge assembly quantities described at the beginning of this section includes multiplication by a single energy balance factor that is a user input, and which should initially be set at 1.000. This factor will need to be subsequently and iteratively changed by the user, as is discussed further in the next section. This is part of the process of assuring an overall energy balance and consistency between the thermal energy implied by the total of projected discharges (MTU times Burnup) and the projections of future total nuclear electric generation that are made by EIA.

The calculation of projected assembly and MTU discharge quantities and the corresponding initial enrichments by cycle is performed on the ASS'YS sheet of the Projection Workbook.

5.5. ADJUSTMENT OF DISCHARGE QUANTITIES BASED ON ENERGY BALANCE

Up to this point in the process, with the energy balance factor set initially by the user at 1.0, the utility five-discharge projections of discharge quantities, timing, and burnup have been adopted without adjustment. The individual plant capacity factors implied by the utility-projected discharge data have also been used as the basis for projection beyond the utility five-discharge projection period. However, for all projection cases, it is essential that the thermal energy generation, the overall projection total of MTU times burnup, be fully consistent with the EIA's independent projection of nuclear electric generation and any related EIA projection of disposal fee revenue. For the cases in which the operating schedules of reactors (shutdown dates) are the same as those of the EIA reference nuclear electric projection, this energy consistency is accomplished by adjusting the amount of all projected discharges (except the first and last for each reactor) such that the energy generation implied by the projection equals the energy generation of the reference EIA projection. For the cases in which the operating schedules of the reactors are different from those of the EIA projection, the adjustment assures that the energy production occurs at the average annual capacity factors of the reference EIA projection. The first utility-projected discharges normally include some energy generation prior to the 1999 start of the projection, and therefore are used without adjustment and are excluded from the energy balance. In addition, some of the energy represented by the core-average burnups after the first discharge was also generated before the first refueling, and therefore must be subtracted from the total thermal energy generation implied by the second through the final full core discharges. The last, full core discharges cannot be adjusted because their amounts are predetermined by core designs. However, the final discharges must be included in the energy balance. The energy balance is performed in four steps as follows:

1. From the EIA nuclear-electric projection considered to be the "reference" projection, the two series of annual values of (1) total nuclear capacity (MWe) and (2) nuclear electricity generation (TWhe) are input by the user. From these, the series of average annual capacity factors are calculated as the simple ratio of the EIA projected generation for each year to the 100 percent generation value. Where the EIA does not cover every year, linear interpolation between known values is used. The EIA

capacity factor for the last year of the EIA projection is extended through to the final shutdown year of the last operating nuclear plant. The result of this calculation is the life cycle time-series of annual capacity factors that is consistent with the appropriate EIA electrical projection. The current reference projection is based on EIA's *Annual Energy Outlook 2002* (EIA 2001), for the period from 1999 to 2020. Because EIA does not project beyond 2020, the average capacity factor for the year 2020 is used as the average capacity factor for each year thereafter. Because of recent actual and expected future NRC-licensed thermal power uprates, a method has been included for incorporating projected future uprates into the projection. Uprated thermal and electrical capacities that have actually been realized or are expected to be realized are entered directly in the REACTOR INPUT spreadsheet towards the bottom of the INPUTS sheet. Projected future uprates can be included as annual capacity factor increments on the lower right hand portion of the NOTES sheet. These uprates are not reactor-specific and are in effect spread across all reactors, achieving in aggregate the additional SNF discharges associated with future projected uprates.

2. The total annual electric generation at 100 percent capacity factor of all nuclear plants in the projection is determined, including allowance for partial-year operation as plants shut down. These annual totals are then multiplied by the reference EIA capacity factors for the same year, yielding the projected annual nuclear electric generation for the projection, and the projected annual disposal fee revenue at 1 mill/kwh and a user-specified ratio of energy sold to energy generated, currently 0.95.

3. The total annual thermal energy generation of the nuclear plants operating at 100 percent capacity factor is determined, including an allowance for partial-year operation beginning from the first refueling shutdown and allowing for partial-year operation as plants shut down. The total annual thermal generation of all reactors is then multiplied by the reference EIA capacity factors for the same year, to give the life-cycle time series of annual thermal energy generation consistent with the appropriate EIA electrical projection. The overall total thermal energy generation, corresponding to the total electrical generation consistent with the EIA electrical projection, is the arithmetic sum of the foregoing annual thermal generation over all years in the projection.

4. The total thermal energy production (MWd) implied by all projected discharge quantities (MTU) and burnups (MWd/MTU) is now calculated. This total is the sum over all projected discharges (except the first), for all reactors. It is also necessary to subtract the energy represented by the core-average burnup following the first discharge because that energy was generated prior to the start of the energy balance.

The thermal energy in individual discharges (MWd) is: MTU discharged x Burnup. The total thermal energy (T) from all discharges (MWd) is determined from:

$$T = T_d + T_f - T_1 \qquad \text{(Eq. 11)}$$

Where:

T_d = Sum of the thermal energy from all discharges from the second utility-projected discharge through to the pre-final discharge for all reactors.
T_f = Sum of the thermal energy from final discharges for all reactors.
T_1 = Sum of the previously-generated initial-core thermal energy, immediately after the first utility-projected refueling, for all reactors.

The core-average burnup after the first refueling, $B_{1,av}$, is given by:

$$B_{1,av} = (1-F_1) \times B_1/2 . \tag{Eq. 12}$$

Where:
F_1 is the refueling fraction of the first utility-projected discharge
B_1 is the batch-average burnup of that first discharge.

The energy balance is achieved by requiring that T, the total thermal energy from all discharges, be equal to the EIA-related total thermal generation (as determined in Step 4, above) of the reactors operating at the EIA capacity factors. This is performed in the ENERGY sheet, after the user has initially set the energy balance factor to 1.0 at the top of the ASS'YS sheet, as mentioned above in Section 5.4. As a result of the initial energy calculation, a multiplying factor on the prior energy balance factor is determined and a new estimate of the energy balance factor is provided at the bottom of the ENERGY sheet. The user then manually inserts this new estimate at the top of the ASS'YS sheet, a new energy balance is performed, and a new energy balance factor estimate is calculated. This process is repeated iteratively until the multiplying factor between iterations (see below) approaches 1.000, the successive energy balance factor estimates converge, and the user is satisfied that an appropriate energy balance has been achieved. The new estimate of the energy balance factor is calculated from the old estimate as follows:

Multiplying Factor = $1 - \Delta/T_d$

New Energy Balance Factor = Multiplying Factor x Old Energy Balance Factor

Where: $\Delta = T -$ (total thermal energy needed to generate EIA-based total electric generation)

The specific EIA nuclear electric projection used for the 2002 Reference Case discharge projection summarized in Section 6 is from the most recent of EIA's annual energy projections, *Annual Energy Outlook 2002* (EIA 2001). This projection assumes the early shutdown of 3 units and the 20-year extension of NRC operating licenses for 45 units. These EIA estimates of nuclear electric generation are converted to annual-average capacity factors, for ease in making other input assumptions, such as the number of license renewals. The plant electric capacities are the Net Summer Electric values (DOE 1999) used by EIA for their projections, updated to reflect subsequent NRC-licensed thermal power uprates.

The calculation of the total thermal energy implied by SNF discharge quantities and burnups is performed on the ASS'YS sheet of the Projection Workbook. The calculation of EIA-related electrical and total thermal energy and the estimates for the new energy balance factor take place on the ENERGY sheet. The iteration described above takes place between ASS'YS!F9 and ENERGY!J246. Once the energy balance has been achieved, the discharged assemblies, MTU, and enrichments are summarized for each reactor on a calendar year basis on the ASSYMTU sheet of the Projection Workbook.

5.6 PROVIDE FOR LIMITED PLUTONIUM RECYCLE

In connection with the national program for disposition of surplus weapons plutonium, the consortium of Duke Power, Cogema, and Stone & Webster have entered into a contract with DOE. This contract provides for the prospective recycle of 25 metric tons of surplus weapons plutonium in Duke Power's Catawba 1 and 2 and McGuire 1 and 2 units during the period 2007 through 2023. The recycling plan, related fuel quantities, and expected discharge burnups (Duke 1999) have been included in this calculation method and its associated projection. These data are not subject to the energy balance adjustment, but their energy production is included in the overall energy balance. The calculations associated with the mixed oxide (MOX) assemblies are in the MOX sheet, and the resultant addition of four data rows, to add MOX fuel as a separate identifiable fuel type in each of two reactors at two sites, is performed in the RESULTS sheet. Additional plutonium may become available for MOX fuel because DOE may not dispose of this plutonium via mixing with vitrified HLW for disposal.

5.7 BURNUP DISTRIBUTIONS

The projection methodology at this point provides the quantity and the batch-average burnup of each discharge. However, each discharge has a spectrum of actual burnups that must be characterized as part of the projection. This section describes the basis for making the burnup distribution, for both the typical discharges and the final, full-core discharges.

A review of historic data on the equilibrium cycle spectrum of burnups associated with an average burnup shows, essentially, a random spectrum of low-skewed, high-skewed, and balanced burnup distributions within discharge batches. This reflects the wide spectrum of operating circumstances to which utility managers are responding at the time of fuel purchases and refuelings. However, if many of these spectra are combined into an average spectrum, an approximately normal and balanced distribution results, with approximately a 15 percent spread above and below the average. Consideration was given to the possibility of randomly generating low-skewed, high-skewed, and balanced distributions. It was concluded that this type of additional detail would not be significant as long as the average distributions were realistic. Note the additional discussion of this issue in the following section. Therefore, it was decided that each normal discharge batch would be split into five components, with the following quantity fractions and burnups relative to the average (based on an analysis of Maine Yankee life cycle discharges):

Table 1. Burnup Distribution Relative To Average Burnup

Fractional Quantity	Relative Avg. Burnup
0.104	0.85
0.216	0.925
0.360	1.00
0.216	1.075
0.104	1.15

For the final core, there are typically three or four groups of fuel with burnups appropriate to one, two, three, etc. cycles of in-core exposure. For purposes of providing a burnup distribution of final core discharges, the full-core quantity was divided into three equal portions with 150 percent, 100 percent, and 50 percent of core-average burnup. Each individual portion is then given the above burnup distribution used for normal discharges. However, each of the three portions of the final discharge has the same single enrichment.

The foregoing burnup distribution calculation, plus the sorting of all the projected discharge data into the input format required for logistics analysis, is performed in a macro that is controlled from the RESULTS sheet of the Projection Workbook. The final results of the macro calculation, which is used as input for logistics analysis, are shown on the spreadsheet entitled OUTPUT.

5.8 GENERAL COMMENT ON THE PROJECTION METHOD

This section comments on aspects of the projection method for which it is recognized that there is above-average probability of disparity between the model's projection and actuality. Four particular aspects are discussed: plant-specific discharges; burnup distributions; enrichment distributions; and the final, pre-shutdown fuel cycle.

Plant-specific Discharges: The output of a projection includes detailed, plant-specific discharge quantities, characteristics and dates. The highly-idealized operating schedule that is assumed and projected for each plant is very unlikely to be realized in practice. At the individual plant level, there are many events that can impact planned operating schedules. These include unplanned maintenance outages and unforseeable utility system changes that can increase or decrease the demand on individual plants. Utility nuclear fuel managers will normally adjust refueling dates and/or the number of discharged assemblies to accommodate these unknowable events as they occur. As a result, plant-specific discharge dates, discharge quantities and characteristics will begin deviating from their projected values with the first (utility-projected) discharges, and will deviate to progressively greater degreees with successive discharges. Thus, the detailed plant-specific discharge data is highly unlikely to conform with actual discharges. However, the historic data on total generation, total discharge quantities and characteristics does incorporate the aggregate impacts of operational upsets. Because the projection process is basically an extrapolation of these historic aggregates, the projected quantities also reflect an impact of prospective future operational upsets, in the aggregate. It is important to note that the projection of discharges is one step removed from the projection of SNF deliveries to the repository, a projection which is needed as input to the repository design process. In effect, the details of individual reactor discharges are highly filtered in the process of selecting reactors to make deliveries and then selecting specific SNF assemblies for delivery. Thus, from the perspective of repository design, the most important characteristics of the discharge projection are the aggregate annual discharges and their average characteristics and variability, rather than reactor-specific discharges.

Burnup Distributions: Historical data on burnup distributions associated with a single discharge show a much greater random and skewed variability than is provided by the regular balanced distribution described in the preceding section. These variations result from unpredictable events that occur during reactor operations, which randomly increase or decrease the amounts of cycle energy generation from what was planned, generally complicating the fuel cycle. The projection methodology used under-predicts the number of outliers within the burnup spectrum of single batches. Therefore, there are likely to be more anomalously hot and cold assemblies than are projected.

Enrichment Distributions: The historical data on enrichment versus discharge burnup exhibits a surprisingly wide band of variance from average enrichments. Again, this is mostly the result of random operating circumstances and utility managers' responses to these circumstances. The projection methodology does not attempt to replicate this variability. The principal implication of this will be associated with criticality. Specifically, at any specific enrichment, there will be more assemblies with both higher and lower burnups than are projected. The assemblies with higher burnup will not be of relative criticality concern. However, those with lower burnups may create more criticality difficulties in burnup credit situations than are inferred from the projection.

Final, Pre-shutdown Fuel Cycle: It is not clear how the utilities will schedule and control the reload quantities in the one or two refuelings that precede the final shutdown and full-core discharge. There is no historic data on this issue because none of the power reactor shutdowns to date have anticipated their shutdown with enough lead time to pursue the most economic shutdown fuel cycle. There are basically two issues: how will the refueling intervals be adjusted to avoid unreasonably short intervals prior to shutdown, and how will the refueling fractions and enrichments be specified so as to minimize the total of pre-shutdown fuel cycle and refueling outage costs? The projection method basically maintains the full utility-indicated refueling duration up to the pre-final refueling, and then discharges a quantity of fuel in proportion to the duration of the last one or two cycles. The current method does not reduce enrichments for those discharge portions of the final core that have received only one or two cycles of exposure. To the extent that some enrichment reduction ultimately takes place in practice, there may prove to be less high-enriched, low-burnup fuel than projected.

Users of the projection data, particularly criticality designers, should be aware of these limitations of the projection method and the ensuing results, and should evaluate possible impacts for their particular application.

6. RESULTS

The results of the characterization of the utility discharge projections are contained in the Excel workbook file FINAL_UTIL_SNF_PROJ_1998.xls. The detailed results of the calculations of projected life cycle SNF discharges and characteristics, including the discharged assemblies, MTU, enrichments, and discharge dates are summarized for each reactor on a calendar year basis on the RESULTS sheet of the Projection Workbook. These same results, in the input format required for waste selection and logistics analysis, are shown on the OUTPUT sheet of the Projection Workbook. The SNF discharge projection that is consistent with the EIA electrical generation assumptions described above in Section 5.5, considered to be the Reference Case for this report, is contained in the electronic file LE45_CP00_BE_R10_2002REF.xls. The two Excel files in electronic form are recorded on a Compact Disk that is identified in Appendix C of this report, and included in the record package for this report.

The following table summarizes historical SNF discharges, the projected SNF discharges for the Reference Case projection, and the resulting projected total SNF discharges. Note that the summary totals for MTU and Assemblies do not add horizontally because the projection data and the total data have been rounded to the nearest 100 units. The average burnups are MTU-weighted and thus do not directly add, numerically.

Table 2. Summary of Historical and Projected SNF Discharges

Characteristic		Historical 1968 - 1998	Projected After 12/98	Total
MTU	BWR	13,784	22,300	36,100
	PWR	24,599	42,700	67,300
	Total	38,383	65,000	103,400
Assemblies	BWR	76,495	128,600	205,100
	PWR	57,255	97,600	154,900
	Total	133,750	226,200	360,000
Average Burnup (MWd/MTU)	BWR	26,214	44,400	37,500
	PWR	34,127	48,800	43,400
	Overall	31,285	47,300	41,300

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7. ADJUSTMENTS TO INPUT DATA

A review of the final EIA RW-859 data (CRWMS M&O 2001c) revealed that some data items still appeared to be anomalous with respect to parallel, related data. Items that were changed to provide the desired internal data consistency are as follows:

- A group of 24 assemblies from the first utility-projected discharge of South Texas 1 was transferred to the second utility-projected discharge.
- A group of 28 assemblies from the third utility-projected discharge of Davis-Besse was transferred to the second discharge.
- The blank assembly weight for one group of assemblies in the fifth utility-projected discharge for Palo Verde 1 was filled using the same assembly weight as used for all of the other projected discharges.
- An anomalous change from 62 assemblies to 26 assemblies that appeared in the final EIA data for the fifth utility-projected discharge for Diablo Canyon 2 was reversed to retain the original value of 62 assemblies to maintain consistency with prior discharges.
- To correct a late-discovered anomaly, the burnup of a 1-assembly discharge in each of the five utility-projected discharges for Prairie Island 1 was changed from 15 to 51 GWd/MTU. This change was also consistent with similar 1-assembly discharges in Unit 2 that had burnups of 54 GWd/MTU. Also, one assembly from Turkey Point 4, with virtually all data missing, was deleted.

These adjustments are further described in the *Report on the Final 1998 RW-859 Data Set* (CRWMS M&O 2001c).

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8. REFERENCES

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor) 1996. *Report on the Development of the 1996 Extended Utility Spent Fuel Projection and a Comparison with the 1995 DOE/EIA Spent Fuel Projection, September 1996.* Vienna, Virginia: CRWMS M&O. ACC: MOV.19961009.0047

CRWMS M&O 2001a. *Calculation Method for the Projection of Future SNF Discharges.* TDR-WAT-NU-000002 Rev 00. Washington DC: CRWMS M&O. ACC: MOV.20010419.0003

CRWMS M&O 2001b. *Technical Work Plan for: Waste Acceptance, Standard Contract Maintenance and Management.* TWP-WAT-NU-000001 REV 00. Washington D.C.: CRWMS M&O. ACC: MOV.20010105.0002

CRWMS M&O 2001c. *Report on the Final 1998 RW-859 Data Set.* TDR-WAT-NU-000003 REV 00. Washington D.C.: CRWMS M&O. ACC: MOV.20010201.0005

DOE (U.S. Department of Energy) 1997. *Nuclear Power Generation and Fuel Cycle Report, 1997.* DOE/EIA-0436(97). Washington, DC.: U.S. Department of Energy, Energy Information Administration. ACC: MOL.20010727.0156.

DOE 1999. *Inventory of Electric Utility Power Plants in the United States 1999, (with data as of January 1, 1999).* DOE/EIA-0095(99). Washington, D.C.: U.S. Department of Energy, Energy Information Administration. TIC: 247313

Duke 1999. *Mission Reactors Irradiation Plan.* DCS-IS-1999-001. Charlotte, North Carolina: Duke Cogema Stone & Webster. TIC: 247642

EIA 2000a. *Final 1998 RW-859 Database, Rev. 1.* Washington, D.C.: U.S. Department of Energy, Energy Information Administration. ACC: MOV.20000714.0015

EIA 2001. *Tables A8 and A9, Annual Energy Outlook 2002, 12/21/2001.* DOE/EIA-0383(2002). Washington, D.C.: U.S. Department of Energy, Energy Information Administration. ACC: MOV.20020123.0001

NRC 2000. *Information Digest, 2000 Edition.* NUREG-1350, Volume 12. Washington D.C.: U.S. Nuclear Regulatory Commission. TIC: 231071.

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APPENDIX A

THE IMPACT OF ECONOMIC, FUEL CYCLE, AND OPERATIONAL FACTORS ON NUCLEAR FUEL BURNUP

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THE IMPACT OF ECONOMIC, FUEL CYCLE, AND OPERATIONAL FACTORS ON NUCLEAR FUEL BURNUP

The purpose of this Appendix is to summarize and quantify the interaction of the principal factors that influence the target discharge burnup of nuclear fuel. The intent is to provide insight into utility incentives and constraints on achieving increases in fuel burnup, as guidance in the projection of future nuclear fuel discharge burnups. Observations and conclusions are provided.

Background

The average burnup of SNF discharged from reactors that are not in their startup cycles has increased at a fairly steady rate. The following table identifies the actual annual average burnups for all U.S. reactors over the 1990 to 1998 period, during which very few reactors were still operating in their startup cycles (EIA 2000a).

Table A-1. Historical Average Burnup in MWd/MTU

Year	BWR Burnup	PWR Burnup	Overall Burnup
1990	25,010	34,235	31,498
1991	28,258	35,515	33,189
1992	29,169	36,612	34,336
1993	30,590	39,029	36,326
1994	33,371	40,177	37,724
1995	33,082	40,510	38,121
1996	35,064	39,026	37,611
1997	35,887	40,164	38,865
1998	36,317	43,181	40,413
Best-Fit Annual Increase	4.52%/yr	2.47%/yr	2.88%/yr

Projections of future burnups made by the utilities as part of the periodic RW-859 surveys also exhibit an upward burnup trend for projected discharge burnups, as evident in the most recent (1998) RW-859 survey (EIA 2000a):

Table A-2. Utility-Projected Average Burnup in MWd/MTU

Year	BWR Burnup	PWR Burnup	Overall Burnup
1999	37,219	43,446	41,497
2000	38,123	44,857	42,431
2001	40,310	45,183	43,422
2002	40,933	46,750	44,937
2003	42,591	46,284	45,017
2004	42,787	46,922	45,481
2005	42,607	46,791	45,380
2006	44,173	47,403	45,918
Best-Fit Annual Increase	2.38%/yr	1.11%/yr	1.42%/yr

Burnups have increased at almost 3 percent/yr in the last 9 years of the historic period and the utilities are projecting about a 1.4 percent/yr increase for the subsequent 8 years. The increase rate for BWRs has been about double that of PWRs, but from a lower base, such that BWRs continue to have lower discharge burnups than PWRs.

Deregulation of the nation's electric utilities is resulting in favorable changes for nuclear electric generation by existing nuclear plants. The main incentive for the use of nuclear power has always been low fuel costs, considerably lower than the principal alternatives, which are fossil-fuelled. Prior to deregulation, the benefits of nuclear fuel cost reductions went primarily to the ratepayers via fuel adjustment clauses in the rate structure. With deregulation, most of the future benefits of fuel cost reductions will go directly to the utilities, both via direct fuel cost savings and by increased nuclear power generation through additional displacement of fossil generation. Thus, deregulation has created direct utility incentives to operate nuclear units at even higher capacity factors, and to reduce nuclear fuel costs even further, to the lowest practicable levels. Therefore, there appear to be sound, fundamental reasons to project a continuation of the historic pattern of increasing discharge burnups.

As noted, the primary reasons for the steady burnup increases are economic: nuclear fuel costs decline with increasing burnup. The principal limitation on the rate of increase is the continuing need to demonstrate that fuel rod integrity can be maintained as design burnups and in-core residence times are increased. However, assuming that fuel integrity can continue to be demonstrated at progressively higher burnups, there are other constraints and limitations on the extent of burnup increases:

- Economic limits are imposed by increased fuel investment costs for the higher enrichments that are needed to produce the higher burnups. There is an economic optimum burnup, beyond which fuel costs increase with increasing burnup. Also, as the economic optimum burnup is approached, the incentives for additional burnup increases become progressively less.

- There is currently an enrichment limit of 5 percent imposed primarily by criticality considerations in the design and NRC licensing of nuclear fuel fabrication plants. Until this limit is increased, it imposes a de facto limit on average burnups in the range of 57,000 to 62,000 MWd/MTU, depending upon cycle duration and reactor type. If this current enrichment limit were raised to 5.5 percent, the enrichment-limited average burnup could increase by as much as an additional 10,000 MWd/MTU.

- Long cycle durations between refuelings minimize the combined costs of refuelings plus the large makeup power costs that are incurred when nuclear units are off-line. However, long durations between refuelings require a higher enrichment to achieve the same burnups, and therefore increase fuel costs. Also, at high plant capacity factors, the combination of the 5 percent enrichment limit and the higher enrichment required for longer cycles imposes a limit on achievable fuel burnup, which, in effect, increases fuel costs. In spite of these fuel cost increases, there can be a net overall cost saving with the longer cycles.

In order to quantify the incentives for, and the limitations on, fuel burnup increases, an evaluation of nuclear fuel and refueling operations costs was performed, and is described in the following section.

Sensitivity of Nuclear Generation Costs to Economic, Fuel Cycle, and Operational Factors

The purpose of this section is to quantify the dependence of nuclear fuel and nuclear plant refueling outage costs on fuel burnup and its interaction with the various fuel cycle and operational constraints outlined above. This is done by first developing nuclear fuel costs as a function of burnup for various refueling intervals, and for various average capacity factors and fuel financing rates. These data are then constrained by enrichment limits and combined with the cost of refueling outages to develop insights as to the relative importance to generation cost of the various constraints and increased burnup. Observations on the incentives for burnup increases up to and beyond the current EPRI target burnups are developed.

Fuel Cycle Cost and Initial Enrichment Dependence on Burnup

Nuclear fuel costs covering a burnup range of 30,000 to 90,000 MWd/MTU were developed for PWRs on 18 and 24 month refueling cycle durations, and for BWRs on 24 and 30 month cycle durations. The calculation of nuclear fuel costs was facilitated by using the small BASIC computer program listed in Appendix B. The assumed thermal efficiency was 32 percent and the core-average specific powers were assumed to be 38.17 kwt/kgU for PWRs and 27.54 kwt/kgU for BWRs. The EIA correlation of the dependence of enrichment on burnup described in Section 5.4 was used to determine the appropriate enrichment needed to achieve each of the burnups. The reference cost inputs assumed approximate current market costs for uranium ($14/lb U_3O_8), conversion ($5/kgU), enrichment ($90/kgSWU), fabrication ($200/kgU), and post-discharge dry storage ($100/kgU). Fuel financing via fuel leasing at 8 percent/yr, and an average capacity factor of 85 percent were assumed. The latter is consistent with recent EIA long-term projections of nuclear generation, but is less than the most recent EIA projections. Cost sensitivity assessments were done for higher fuel financing rates, higher and lower capacity factors, and for increased uranium and/or enrichment costs relative to the other market costs. In order to evaluate the net incentives for longer cycle durations and their impact on fuel burnups, the direct costs of refueling outages and for makeup energy costs during refueling outages were also estimated.

The nuclear fuel costs resulting from the foregoing assumptions are shown in Figures A-1 and A-2 for BWRs and PWRs respectively. The initial enrichments needed to attain the desired burnups are also shown. The fuel costs are similar for BWR and PWR and have the same basic dependence on fuel burnup. The BWR costs show a minimum in the range of 80,000 to 85,000 MWd/MTU; the PWR indicates a minimum in the range of 90,000 MWd/MTU, under current economic conditions.

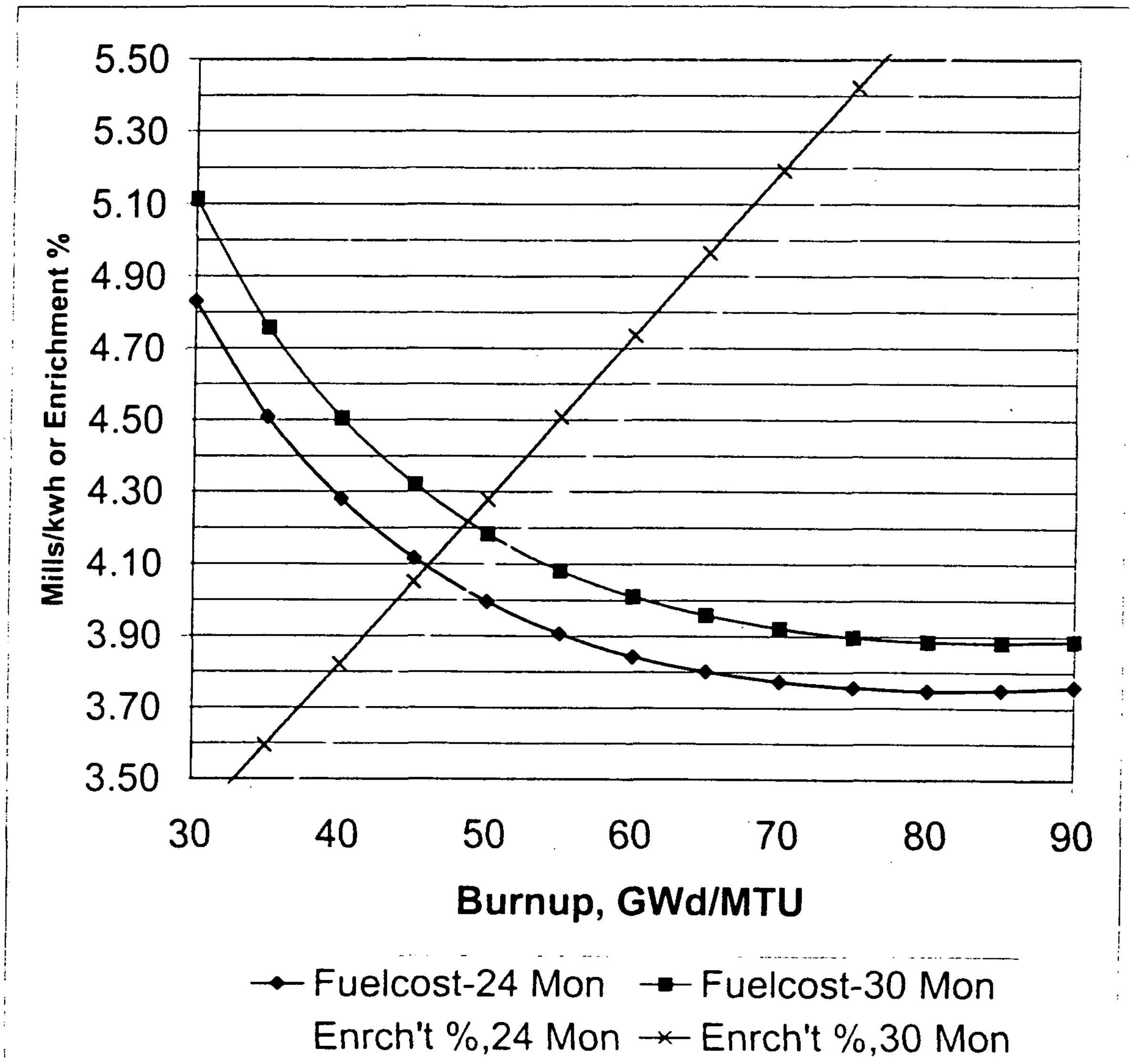

Figure A-1. Boiling Water Reactor Fuel Cost and Enrichment

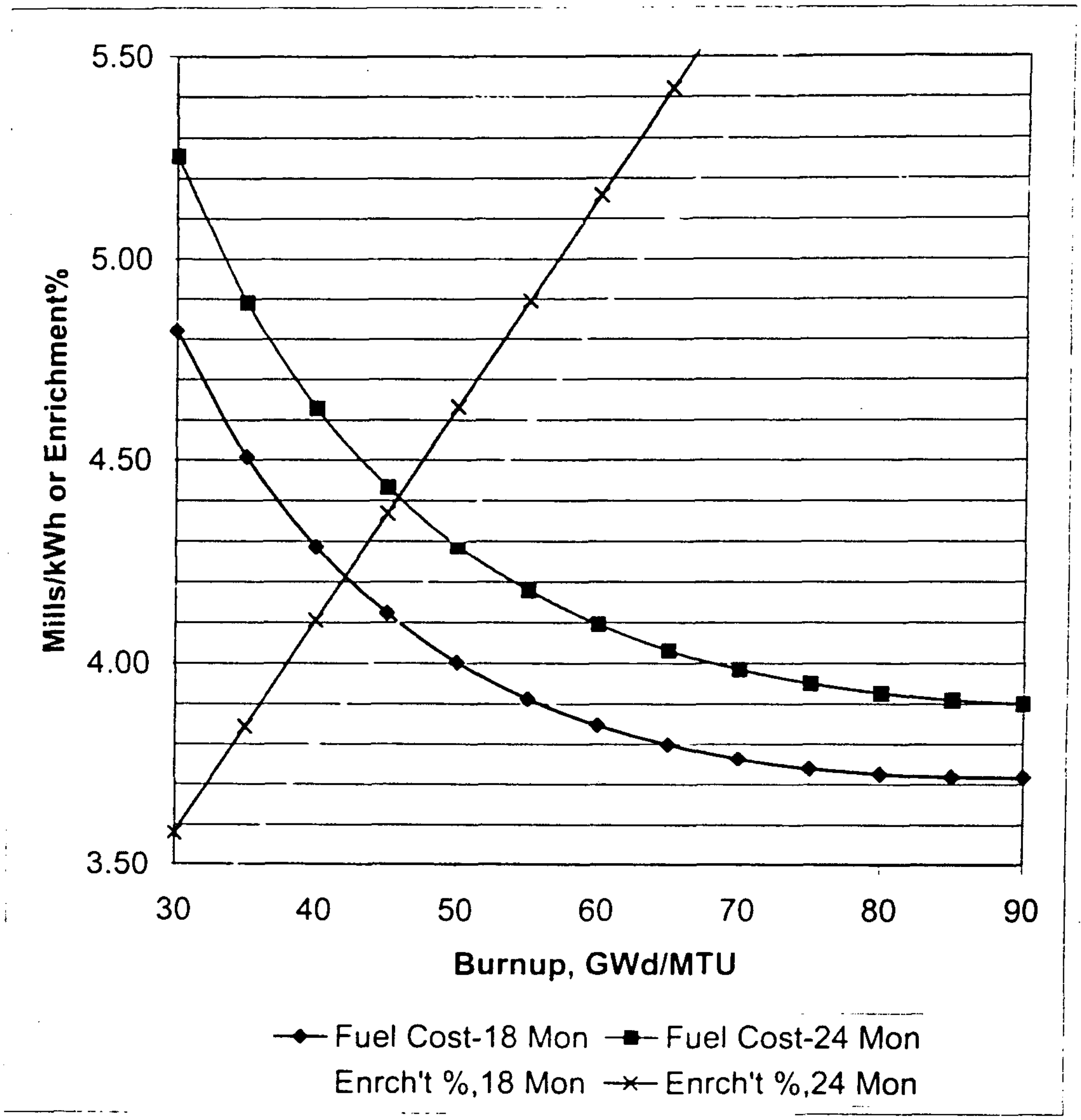

Figure A-2. Pressurized Water Reactor Fuel Cost and Enrichment

There are three specific features, common to both reactor types, that should be noted:

1. Fuel costs become very insensitive to burnup as the minimum fuel cost is approached. It can be shown that fuel costs are within 1 percent of the minimum cost at about 83 percent of the burnup at which the minimum cost is achieved, and are within 0.5 percent of the minimum cost at about 88 percent of this economically-optimum burnup. It is thus apparent that burnups in the range of 85 to 90 percent of the optimum would realize all but a small portion of the benefits of going to the optimum burnup.

2. The longer cycle durations result in higher fuel costs for the same burnups, an effect that is due to the higher enrichments needed for the longer cycles, also shown on the figures. This amounts to 0.15 to 0.2 mills/kWh for the BWRs (going from a 24- to a 30 month cycle) and 0.2 to 0.3 mills/kWh for the PWRs (going from an 18- to a 24 month cycle). A 0.2 mill/kWh increase equates to a $1.5 million/yr increase in fuel costs for a 1000 MWe unit at 85 percent capacity factor. Consequently, these increases are significant, and can be justified only if there are even larger savings from the reduced number of refueling outages with the longer cycles.

3. The burnups attainable with initial enrichments of 5.0 percent are considerably lower than the optimum burnup (obtainable with higher initial enrichments) at which the minimum fuel cost is realized. This is discussed further in the following paragraphs.

Burnup Constraints Due to Enrichment Limits

The current nuclear fuel fabrication plant license limit of 5.0 percent initial fuel enrichment will ultimately limit the burnups that can be achieved. Raising this limit to 5.5 percent would be of benefit, and in fact, the U.S. Enrichment Corporation has requested and received an NRC license revision for its Paducah enrichment plant with a 5.5 percent maximum enrichment. The EIA enrichment-burnup correlation (Section 5.4) can be used to estimate the maximum batch-average burnup that can be achieved with a given batch-average enrichment. However, because of recent fuel assembly design innovations, this enrichment correlation must be used with care. For example, many fuel designs use natural uranium axial blankets, short sections at the ends of each rod that replace enriched uranium with natural uranium in the low-burnup end portions of the rod. In applying the enrichment-burnup correlation to estimate enrichment-limited burnups, these axial blankets have been excluded when computing the assembly-average enrichment. Also, BWR fuel designs use a number of additional techniques, including multiple enrichments within rods and different average rod enrichments within fuel assemblies. Because of the proprietary nature of these designs, the information needed to quantify the ratio of peak pellet enrichment to assembly-average enrichment is not available. It has therefore been assumed in the following section, for purposes of applying the BWR burnup-enrichment correlation to estimate BWR enrichment-limited burnups, that the assembly-average enrichment excluding the axial blanket sections is 0.5 percent less than the maximum pellet enrichment in the assembly. Specifically, the BWR burnup limit for maximum (pellet) enrichments of 5.0 percent and 5.5 percent is assumed to occur at 4.5 percent and 5.0 percent enrichments, respectively (illustrated in Figure A-1).

Financial Incentives and Physical Constraints on Increased Burnup

In summary, the following Table A-3 shows BWR and PWR burnup data that is relevant to the financial incentives for increasing burnup, and the various factors and constraints that may impose limits on achievable average burnups. The table first shows the average burnups of actual 1998 BWR and PWR discharges and the average BWR and PWR burnups that would be achieved assuming the goals of the EPRI Robust Fuels Project are met. The table next shows the maximum achievable batch-average burnups for BWRs and PWRs operating at 85 percent capacity factors with 5 percent and 5.5 percent maximum initial fuel enrichments. And finally, the table shows the burnup that achieves a fuel cost that is within 1 percent of the minimum fuel cost, which occurs at about 83 percent of the related optimum burnup at the minimum-cost point.

Table A-3. Average Burnup Data

Reactor Type	Cycle Duration (months)	Average Burnup (MWd/MTU)				
		1998 Avg. Burnup	EPRI Target	Burnup @ 5.0% Max.	Burnup @ 5.5% Max.	Burnup @ 83% Bopt*
BWR	24	36,300	57,000	59,000	70,000	68,000
	30	36,300	57,000	55,000	66,000	70,000
PWR	18	43,200	62,000	63,000	72,000	75,000
	24	43,200	62,000	57,000	67,000	75,000

*Bopt = optimum burnup

The above table shows that the majority of the burnup increases are realized in going from the 1998 average burnups and reaching the EPRI target burnups. The table also indicates that the EPRI target burnups are generally compatible with the current 5 percent enrichment limitation of the fuel fabrication plants, for the predominant cycle durations of 24 months for BWRs and 18 months for PWRs. However, with the 5.0 percent enrichment limit, PWRs operating on a 24 month cycle will be limited to burnups that are about 5,000 MWd/MTU below the EPRI target burnups. The table also indicates that going to a 5.5 percent enrichment adds about 10,000 MWd/MTU to the enrichment-limited burnups. Further, with the 5.5 percent enrichment, the achievable burnups are more comparable to the burnups (83 percent Bopt) at which fuel costs are within about 1 percent of minimum fuel costs. Achievement of absolute minimum fuel costs would require an additional 20 percent burnup increase and enrichments in the range of 6.5 percent, and is thus not a practicable goal under current economic conditions. Finally, a 6 month increase in the predominant cycle durations, to 30 months for the BWR and 24 months for the PWR, reduces the achievable burnups with the 5 percent or 5.5 percent enrichment limits by about 5,000 MWd/MTU.

In order to quantify the financial incentives for going to the EPRI burnup targets (or the 5.0 percent limit, if lower) and the additional incentive for increasing the maximum enrichment from 5.0 percent to 5.5 percent and adding about 10,000 MWd/MTU to the average burnup, the evaluated fuel costs are shown, and these are translated into annual dollar differences for a 1,000 MWe nuclear plant operating at 85 percent capacity factor. The fuel costs in mills/kWhe are as follows:

Table A-4. Nuclear Fuel Costs, Mills/KWHE

Reactor Type	Unit Fuel Cost in Mills/kWhe			
	Cycle Duration (months)	@1998 Avg. Burnup	@EPRI/5% Burnup	@5.5% Max. Burnup
BWR	24	4.440	3.881	3.773
	30	4.682	4.085 (5%)	3.954
PWR	18	4.180	3.828	3.751
	24	4.500	4.146 (5%)	4.017

The annual financial incentives that correspond to the above fuel costs for going from the 1998 to the EPRI/5 percent burnups and for then going to the burnup at the 5.5 percent enrichment limit are shown below for a 1000 MWe nuclear plant operating at 85 percent capacity factor.

Table A-5. Annual Fuel Cost Savings ($M/YR)

Reactor Type	Annual Fuel Cost Savings ($M/YR)		
	Cycle Duration (months)	From 1998 Avg. Burnup to EPRI/5% Burnup	From EPRI/5% Burnup to 5.5% Max Burnup
BWR	24	4.17	0.80
	30	4.44	0.98
PWR	18	2.62	0.57
	24	2.64	0.96

The above estimates confirm the substantial financial incentives for increasing fuel burnups from their 1998 average levels to the EPRI burnup targets. Given the magnitude of these incentives, it appears reasonable to project progressive increases in current burnups at rates that will result in the initial realization of the EPRI discharge burnups beginning in about 2015. This provides the time necessary to begin achieving these high burnups and to make any design adjustments necessary to limit fuel failure rates. The principal uncertainty in this projection arises from the small but finite possibility that the fuel cladding and fuel assembly structure cannot be designed and fabricated to sustain these higher burnups at acceptably low failure rates, and with tolerable fuel-related operating constraints.

There are about $0.5 to 1 million/yr (per 1000 MWe) in fuel cost incentives to increase the current 5.0 percent fuel fabrication enrichment limit to 5.5 percent and to ultimately go beyond the current EPRI target burnups by approximately the additional 10,000 MWd/MTU achievable with the 5.5 percent limit. This is probably a sufficient incentive to justify the necessary additional fuel testing, if and when it becomes realistic to do so. Thus, this analysis indicates the possibility of ultimate burnup increases of an additional 10,000 MWd/MTU in the very long term. However, this possibility depends on the favorable resolution of three current uncertainties: an increase in fuel fabrication plant NRC-licensed enrichment limits; the large-scale demonstration of acceptably low fuel failure rates at the EPRI burnup targets; and the subsequent demonstration of the viability of achieving an additional 10,000 MWd/MTU. It also depends upon little deterioration in economic incentives, such as those caused by large increases in uranium and/or enrichment costs, relative to fabrication costs. Given these uncertainties, and the relatively long time to resolve them, it does not appear prudent to project SNF discharges above the EPRI target burnup levels at this time. However, the incremental cost of additional shielding is quite small if included in the original construction. Therefore, the current designers of fixed facilities should consider the possibility of handling peak assembly burnups of up to about 85,000 MWd/MTU, with correspondingly high neutron outputs, in establishing the shielding design and/or related operational work-around requirements for fixed facilities.

The foregoing observations as to the incentives for burnup increases up to and possibly beyond the EPRI target burnups have been illustrated with a specific set of assumptions. It is important to note that these observations do not depend significantly on fuel cycle or fuel supply cost assumptions over a considerable range of such assumptions. Higher interest rates for financing nuclear fuel inventories, and lower capacity factors result in higher fuel costs, and to a lesser extent also reduce the optimum burnup level at which minimum fuel costs are realized. A general price increase that impacts all costs about equally would increase fuel costs, but would not alter the optimum burnups. In the more extreme circumstances of high interest rates, and doubling the costs of uranium and enrichment relative to the other costs, optimum burnups decrease to the level of the EPRI target burnups, but the basic incentives still justify approaching the EPRI burnup goals. Because optimum burnups under current typical conditions are well above current enrichment-limited target burnups, reductions in optimum burnups reduce the incentives somewhat, but not significantly enough to suppress the goal of attaining the EPRI target burnups. Conversely, utilities use a number of tactics to reduce nuclear fuel and total generation costs, such as reducing interest rates for fuel via fuel leasing, increasing plant capacity factors by economic dispatch, increasing cycle durations, and containing the costs of fuel materials and fabrication by competitive procurement. All of these tactics result in increasing the incentives for realizing the EPRI burnup targets. It would thus require truly major changes, such as very large increases in uranium and enrichment costs relative to fabrication costs, to materially change the current significant financial incentive for achieving EPRI target burnups. In that regard, it is noted that in the past, uranium prices have been much higher than the current levels, which are close to all-time lows on an inflation-adjusted basis.

Incentives to Increase Refueling Cycle Durations

The preceding data on fuel costs includes data on both the dominant current cycle durations (24 months for BWRs and 18 months for PWRs) and cycle durations that are 6 months longer. The longer cycles have a higher fuel cost of about 0.2 mills/kWhe ($1.5 m/yr) for BWRs and 0.3 mills/kwhe ($2.2 m yr) for PWRs at the EPRI target burnups, due to the higher enrichments needed for the longer cycles. However, if the savings from the reduced numbers of refuelings with longer refueling cycles are greater than the increase in fuel costs, going to the longer cycles would be justified, assuming that the rate of unscheduled maintenance outages would not increase significantly with the longer cycle durations. In going from a 24- to a 30-month cycle for BWRs, one refueling is saved every 10 years; consequently, the annualized saving of refueling outage cost is one-tenth of the cost of a refueling outage. The corresponding annualized saving in going from an 18 to a

24 month cycle for PWRs is one-sixth of the outage cost. The cost of a refueling outage is made up of two primary components: the direct costs of performing the refueling and maintenance that takes place during the outage; and the costs of makeup energy that must be generated or purchased to offset the energy generation that is lost as a result of the outage.

For example, if the direct cost of a refueling outage were $15 million, and the outage lasted for 24 days, the total annualized outage savings for a BWR going to a 30 month cycle would be $1.5 m plus 2.4 days of avoided makeup energy cost. The corresponding annualized savings for a PWR going to a 24 month cycle would be $2.5m plus 4 days of avoided makeup energy costs. Makeup energy costs are highly utility-specific. However, a typical value of 2.4 cents/kWhe equates to $0.5 m/day for a 1000 MWe unit. Thus the annualized savings for a BWR going to a 30 month cycle would be $1.5m+$1.2m=$2.7m, as compared to the BWR fuel cost penalty of about $1.5m. The annualized savings for a PWR going to a 24 month cycle would be $2.5m+$2.0m=$4.5m, as compared to the PWR fuel cost penalty of about $2.2m. It therefore appears that the annualized savings of increasing the refueling outage by 6 months are about double the fuel cost penalty, with the PWR having a considerably greater absolute annual dollar incentive to lengthen its cycle duration to 24 months. A key assumption in the foregoing is that refueling outages do not cost more nor take longer with increased cycle duration, and that forced outage rates are the same for both cycle durations. However, if the refueling outage with the longer cycles were to cost 10 percent more and last 10 percent longer, the annualized savings from the avoided refueling outages would be reduced by about 40 percent for the BWR, and the net savings would almost vanish. For the PWR, the annualized savings would be reduced by 30 percent, and the net savings would be less than $1m/yr. Similar loss of incentives would occur if forced outage rates were higher with the longer cycles. This suggests that additional experience with the current cycle durations needs to be acquired before there is a sound basis for deciding on further increases in cycle length. PWRs appear to have greater current incentives for achieving 24 month cycles than BWRs have for increasing cycle durations to 30 months.

<u>Summary</u>
The following is a summary of the principal conclusions that have been developed within this Appendix.

1. There is a well-established historic trend of increasing average SNF discharge burnups at a recent rate of more than 2 percent/year. Utilities continue to project increasing burnups in the near term. As of 1998, the average discharge burnups were 36,300 MWd/MTU for BWRs and 43,200 MWd/MTU for PWRs.

2. EPRI's Robust Fuel Project has established demonstration targets that support average discharge burnups of 57,000 MWd/MTU for BWRs and 62,000 MWd/MTU for PWRs. Attainment of these burnups relative to current burnups would result in fuel cost savings in the range of 0.15 to 0.3 mills/kWhe, equivalent to $1.1 to $2.2 million/yr for a 1000 MWe plant. Under ongoing electric utility deregulation practices, these savings would accrue directly to utilities, giving utilities significant incentive to continue to

increase discharge burnups at a rate consistent with demonstrating continuing fuel integrity, and to increase nuclear plant capacity factors.

3. There is a current limit on attainable burnup, imposed by the current 5 percent maximum enrichment in the NRC licenses for nuclear fuel fabrication plants. The EPRI target burnups are generally compatible with the PWR and BWR burnups attainable with the current 5 percent enrichment limit, except that PWRs operating with a 24 month cycle would be limited to burnups that are about 5,000 MWd/MTU below the EPRI PWR target burnups. Because of the compatibility with enrichment limits and the utility financial incentives to increase burnups, the ultimate attainment of EPRI target burnups appears to be a reasonable assumption for the projection of future discharge burnups. The principal uncertainty in this assumption is the small, but finite possibility that the fuel cladding and fuel assembly structure cannot be designed and fabricated to sustain these higher burnups at acceptably low failure rates, and with tolerable fuel-related operating constraints.

4. There appears to be some interest in raising the current enrichment limit to about 5.5 percent, and the United States Enrichment Corporation has received NRC approval for a 5.5 percent limit for its Paducah enrichment plant. The same increase at fuel fabrication plants would permit an increase in discharge burnups of about 10,000 MWd/MTU, and additional fuel cost savings in the range of $0.5 to $1.0 m/yr for a 1000 MWe plant. If this incentive were to persist under future economic conditions, it is probably sufficient to interest at least some utilities. Therefore, there is a possibility that average burnups could ultimately go above the current EPRI targets. However, given the relatively long time for getting to the EPRI target burnups on a significant scale, and then going beyond them, and the related technical and economic uncertainties, it does not appear prudent to project average discharge burnups above the EPRI target burnup levels at this time.

5. The burnups that can be achieved at the 5.5 percent enrichment limit result in fuel costs that are within roughly 1 percent of minimum possible fuel costs under current economic conditions, and could be at or above future minimum fuel costs. The rapidly diminishing incentives and the increased enrichments needed to go to even higher burnups probably mean that the practical upper limit on burnup is the burnup achievable at 5.5 percent enrichment.

6. There appear to be financial incentives for some PWRs to ultimately go to 24 month fuel cycles. The incentives for BWRs to go to 30 month fuel cycles appear marginal, and could be offset by the increased risk of forced outages with the longer periods between major maintenance/refueling outages.

Conclusion

The overall conclusion of this Appendix is that there are a number of fundamental factors favorable to the continued operation of existing nuclear units at high capacity factors, and to the continued reduction in nuclear fuel costs through increased burnup. This supports an assumption that average discharge burnups will continue to increase, ultimately reaching the EPRI target average burnups of 57,000 MWd/MTU for BWRs and 62,000 MWd/MTU for PWRs. The average rate of burnup increase will reflect the time it takes to reach and demonstrate large-scale fuel integrity at higher burnups, and to make and demonstrate the efficacy of any design adjustments that may be necessary. Given that this demonstration process has already been initiated, an assumption that the lead plants will initially achieve the EPRI target discharge burnups by 2015 appears to give sufficient time for such initial demonstration. This timing is achieved with an average burnup increase rate of 1 percent/year, which is less than historical rates, but reflects the decreasing incentives as burnups increase. The principal uncertainty in the assumption of continued burnup increases at 1 percent/yr up to the EPRI targets is the small, but finite possibility that fuel rods and fuel assembly structural components cannot be designed and fabricated to achieve the target burnups at acceptably low fuel failure rates and with tolerable fuel-related operational constraints.

An additional conclusion of this Appendix addresses the issue of the maximum burnup that would be handled at the repository and could therefore be specified for the design of fixed facilities. The assumption that the EPRI target burnups will be achieved with the current 5.0 percent enrichment limit suggests a maximum assembly-average burnup in the range of 71,000 to 75,000 MWd/MTU. However, assuming that the maximum NRC-licensed uranium enrichment will ultimately be raised from the current 5 percent level to 5.5 percent, there appears to be enough additional fuel cost savings to justify a further increase of about 10,000 MWd/MTU in average discharge burnups, if this were to occur under current economic conditions. The uncertainties in the attainability and the timing of such a prospective increase, and the possibility that the current economic incentives would be removed by major relative increases in uranium or enrichment costs, are sufficiently large that it is not prudent to project such an additional increase at this time. Nonetheless, the incremental cost of additional shielding is small if included in the original construction. It would therefore be prudent for the current designers of fixed facilities to consider the possibility of handling peak assembly burnups of up to about 85,000 MWd/MTU, rather than 71,000 to 75,000 MWd/MTU, as the maximum assembly-average burnup, coupled with a suitably short cooling time, such as 5 years.

APPENDIX B

LISTING OF BASIC COMPUTER PROGRAM FOR CALCULATING NUCLEAR FUEL COSTS

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LISTING OF BASIC COMPUTER PROGRAM FOR CALCULATING NUCLEAR FUEL COSTS

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REM NUFUCOST - PROGRAM TO CALCULATE NUCLEAR FUEL COST VS BURNUP
10 DEFINT I-N
20 DIM BURN(13), ENRT(13), TIN(13), FCTR(13), FPRATIO(13), SWUS(13), UCOST(13)
30 DIM ECOST(13), FCOST(13), COSTINIT(13), ONEOVRB(13), REFFRCN(13), BB(13)
40 DIM UNITCU(13), UNITCE(13), UNITCF(13), UNITCS(13), UNITCINV(13), UNITCTOT(13)
50 DIM ENRTBL(11), SWUTBL(6, 11)
52 TU = 1.5: TE = 1!: TF = .5
54 DLRU = 14!: DLRCON = 5!: DLRSWU = 90!: DLRFAB = 200!: DLRSTR = 100
56 ITAIL = 6: ETA = .32: SPECP = 38.17: BORPS = "P"
60 DATA 3.229,4.306,5.414,6.544,7.675,8.851,10.011,11.203,12.383,13.563,14.743
70 DATA 3.061,4.092,5.153,6.236,7.320,8.449,9.563,10.708,11.842,12.976,14.110
80 DATA 2.911,3.900,4.919,5.960,7.003,8.090,9.162,10.265,11.357,12.449,13.541
90 DATA 2.776,3.727,4.708,5.711,6.712,7.756,8.795,9.864,10.918,11.972,13.026
100 DATA 2.653,3.569,4.516,5.484,6.455,7.469,8.469,9.499,10.519,11.539,12.559
110 DATA 2.540,3.425,4.339,5.276,6.216,7.198,8.167,9.165,10.154,11.143,12.132
115 ENRTBL(1) = 2.5: FOR J = 2 TO 11: ENRTBL(J) = ENRTBL(J - 1) + .5: NEXT J
120 FOR I = 1 TO 6: FOR J = 1 TO 11: READ SWUTBL(I, J): NEXT J: NEXT I
122 INPUT "ENTER (IN QUOTES) RUN # (0 FOR NO FILE RECORD),TITLE ", RUNNOS, TITLES
124 INPUT "ENTER INPUT CONTROL INDEX (0 FOR NO CHANGE, -1 TO CHANGEB/P", IXINP
126 IF IXINP = 0 THEN GOTO 160
128 IF IXINP < 0 THEN GOTO 150
130 INPUT " ENTER TU3O8,TENRT,TFAB, IN YEARS = ", TU, TE, TF
140 INPUT " ENTER $ LBU3O8,$ KUCONV,$ SWU,$ KGUFAB,$ KGUSTRG = ", DLRU, DLRCON, DLRSWU, DLRFAB,
DLRSTR
145 INPUT " ENTER INDEX FOR TAILS 1 TO 6 FOR .20,.22,.24,.26,.28, OR .30 = ", ITAIL
150 INPUT " ENTER ETA,KWT KGU,AND B OR P(IN QUOTES) = ", ETA, SPECP, BORPS
160 INPUT " ENTER TCYC (DAYS),CAPFCTR (FRACTION) AND INT RATE (FRACTION/YR) = ", TCYC, CF, RATE
170 BURN(1) = 30!: FOR I = 2 TO 13: BURN(I) = BURN(I - 1) + 5!: NEXT I
175 TAIL(1) = .2: FOR I = 2 TO 6: TAIL(I) = TAIL(I - 1) + .02: NEXT I
180 DELBCYC = SPECP * CF * TCYC / 1000: RATEFCTR = .1141553# / (ETA * SPECP * CF)
182 DRATE = (1 + RATE) ^ (1 / 365) - 1
185 FOR I = 1 TO 13
190 IF BORPS = "P" THEN 210
200 ENRT(I) = 1.018 + .0457 * (BURN(I) + DELBCYC): GOTO 220
210 ENRT(I) = .756 + .0526 * (BURN(I) + DELBCYC)
220 REFFRCN(I) = DELBCYC / BURN(I): TIN(I) = TCYC / REFFRCN(I)
230 FCTR(I) = 2 * (1 / (1 - 1 / ((1 + DRATE) ^ TIN(I))) - 1 / (DRATE * TIN(I)))
240 FPRATIO(I) = (ENRT(I) - TAIL(ITAIL)) / (.7115 - TAIL(ITAIL))
250 INDEX = INT((ENRT(I) - 2.5) * 2) + 1: SWUS(I) = SWUTBL(ITAIL, INDEX) + 2! * (ENRT(I) - ENRTBL(INDEX)) *
(SWUTBL(ITAIL, INDEX + 1) - SWUTBL(ITAIL, INDEX))
270 UCOST(I) = (2.6 * DLRU + DLRCON) * FPRATIO(I) * ((1 + RATE) ^ TU)
280 ECOST(I) = DLRSWU * SWUS(I) * ((1 + RATE) ^ TE)
285 FCOST(I) = DLRFAB * ((1 + RATE) ^ TF)
290 COSTINIT(I) = UCOST(I) + ECOST(I) + FCOST(I)
300 ONEOVRB(I) = 1 / (24 * ETA * BURN(I))
310 UNITCU(I) = UCOST(I) * ONEOVRB(I)
320 UNITCE(I) = ECOST(I) * ONEOVRB(I)
330 UNITCF(I) = FCOST(I) * ONEOVRB(I)
340 UNITCS(I) = DLRSTR * ONEOVRB(I)
350 UNITCINV(I) = RATEFCTR * RATE * (FCTR(I) * COSTINIT(I) - (2 - FCTR(I)) * DLRSTR) / 2!
360 UNITCTOT(I) = UNITCU(I) + UNITCE(I) + UNITCF(I) + UNITCS(I) + UNITCINV(I)
370 PRINT ENRT(I), UNITCTOT(I),
380 NEXT I: PRINT
390 WIDTH "LPT1:", 130
400 LPRINT CHRS(27) + "&l8D", CHRS(27) + "(s20h6V"
404 TITLES = "RUN " + RUNNOS + "  " + TITLES
405 LPRINT TITLES
410 LPRINT " INPUT  TU,TE,TF = ", TU, TE, TF,
420 LPRINT " INPUT  $U,$CON,$SWU,$FAB,$STR = "; DLRU; DLRCON; DLRSWU; DLRFAB; DLRSTR
430 LPRINT " INPUT  TAILS INDEX = "; ITAIL,
440 LPRINT " INPUT  ETA,KW KGU,B/P = ", ETA; SPECP; BORPS,
450 LPRINT " INPUT  TCYC,CF,INT RATE = ", TCYC; CF; RATE
```

```
460 LPRINT "OUTPUTS:    DEL B CYC = "; DELBCYC
470 LPRINT "BURNUPS GWD/MTU"; : FOR I = 1 TO 13: LPRINT USING "  ###  "; BURN(I); : NEXT I: LPRINT
480 LPRINT "REFUELING FRACT"; : FOR I = 1 TO 13: LPRINT USING "  #### "; REFFRCN(I); : NEXT I: LPRINT
490 LPRINT "ENRICHMENT W%  "; : FOR I = 1 TO 13: LPRINT USING " # #### "; ENRT(I); : NEXT I: LPRINT
500 LPRINT "FEED/PRODUCT   "; : FOR I = 1 TO 13: LPRINT USING " ## ####"; FPRATIO(I); : NEXT I: LPRINT
510 LPRINT "SWUS PER KGU   "; : FOR I = 1 TO 13: LPRINT USING " ##.####"; SWUS(I); : NEXT I: LPRINT
515 LPRINT "INVESTT FCTR   "; : FOR I = 1 TO 13: LPRINT USING " #.#### "; FCTR(I); : NEXT I: LPRINT
520 LPRINT "MILLS/KWH, U   "; : FOR I = 1 TO 13: LPRINT USING " ## ####"; UNITCU(I); : NEXT I: LPRINT
530 LPRINT "MILLS/KWH, SWUS"; : FOR I = 1 TO 13: LPRINT USING " ## ####"; UNITCE(I); : NEXT I: LPRINT
540 LPRINT "MILLS/KWH, FAB "; : FOR I = 1 TO 13: LPRINT USING " ## ####"; UNITCF(I); : NEXT I: LPRINT
550 LPRINT "MILLS KWH, STRG"; : FOR I = 1 TO 13: LPRINT USING " ## ####"; UNITCS(I); : NEXT I: LPRINT
560 LPRINT "MILLS KWH,INVTY"; : FOR I = 1 TO 13: LPRINT USING " ## ####"; UNITCINV(I); : NEXT I: LPRINT
570 LPRINT "MILLS KWH,TOTAL"; : FOR I = 1 TO 13: LPRINT USING " ## ####"; UNITCTOT(I); : NEXT I: LPRINT
580 IF RUNNOS = "0" THEN GOTO 695
590 FILENAMS = "A " + BORPS + RUNNOS + ".TXT"
600 LPRINT "RESULTS RECORDED ON "; FILENAMS
610 OPEN FILENAMS FOR OUTPUT AS #1
615 WRITE #1, TITLES
620 WRITE #1, TU, TE, TF
625 WRITE #1, DLRU, DLRCON, DLRSWU, DLRFAB, DLRSTR
630 WRITE #1, ITAIL, ETA, SPECP, BORPS, TCYC, CF, RATE, DELBCYC
640 FOR I = 1 TO 13: BB(I) = BURN(I): NEXT I
650 WRITE #1, "BURNUP, GWD MTU", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
655 FOR I = 1 TO 13: BB(I) = REFFRCN(I): NEXT I
656 WRITE #1, "REFUELING FRACT", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
660 FOR I = 1 TO 13: BB(I) = ENRT(I): NEXT I
661 WRITE #1, "ENRICHMENT, WT%", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
665 FOR I = 1 TO 13: BB(I) = FPRATIO(I): NEXT I
666 WRITE #1, "FEED PRODUCT   ", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
670 FOR I = 1 TO 13: BB(I) = SWUS(I): NEXT I
671 WRITE #1, "SWUS PER KGU   ", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
675 FOR I = 1 TO 13: BB(I) = FCTR(I): NEXT I
676 WRITE #1, "INVESTT FCTR   ", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
678 FOR I = 1 TO 13: BB(I) = UNITCU(I): NEXT I
679 WRITE #1, "MILLS KWH, U   ", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
680 FOR I = 1 TO 13: BB(I) = UNITCE(I): NEXT I
681 WRITE #1, "MILLS KWH, SWUS", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
682 FOR I = 1 TO 13: BB(I) = UNITCF(I): NEXT I
683 WRITE #1, "MILLS KWH, FAB ", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
684 FOR I = 1 TO 13: BB(I) = UNITCS(I): NEXT I
685 WRITE #1, "MILLS KWH, STRG", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
686 FOR I = 1 TO 13: BB(I) = UNITCINV(I): NEXT I
687 WRITE #1, "MILLS KWH,INVTY", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
688 FOR I = 1 TO 13: BB(I) = UNITCTOT(I): NEXT I
689 WRITE #1, "MILLS KWH,TOTAL", BB(1), BB(2), BB(3), BB(4), BB(5), BB(6), BB(7), BB(8), BB(9), BB(10), BB(11), BB(12),
BB(13)
690 CLOSE #1: GOTO 700
695 LPRINT "NO OUTPUT FILE"
700 LPRINT
710 INPUT "ENTER NEXTRUN INDEX (=0 IF NONE) = "; NEXRUN
720 IF NEXRUN > 0 THEN GOTO 122
800 END
```

APPENDIX C

ELECTRONIC FILE RECORD

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ELECTRONIC FILE RECORD

The following table lists the files contained on the compact disk that is part of the record package for this report.

Table C-1. Description of Electronic Files

File Name	File Type	File Size	QA
FINAL_UTIL_SNF_PROJ_1998.xls	MS Excel	2.3 mb	N/A
LE45_CP00_BE-R10_2002REF.xls	MS Excel	20.2 mb	N/A

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